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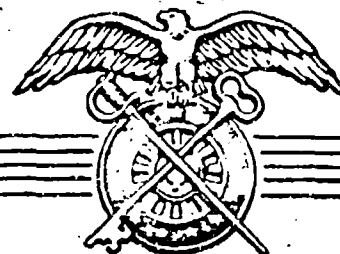
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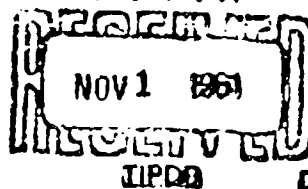
MOISTURE PERMEABILITY INDEX
A NEW INDEX FOR DESCRIBING EVAPORATIVE
HEAT TRANSFER THROUGH FABRIC SYSTEMS

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JUNE 1961



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<p>Quartermaster Research & Engineering Center, Natick, Mass. MOISTURE PERMEABILITY INDEX - A NEW INDEX FOR DESCRIBING EVAPORATIVE HEAT TRANSFER THROUGH FABRIC SYSTEMS BY A. E. Woodcock, 16 pp., illus. (Technical Report EP-148) June 1961</p> <p>From theoretical considerations a new clothing parameter, moisture permeability index, has been developed. The existing "clo" formula relating dry clothing insulation and ambient temperature to man's heat loss has been extended to include evaporative heat transfer. This extension indicates a range over which the clothed man may maintain thermal equilibrium. This concept of range applies in all types of environments and thus one theory is applicable to hot, temperate, and cold environments. The theory also indicates the limitations of sweat evaporation as a cooling mechanism.</p> <p>A method is described for measuring moisture permeability index.</p>	<p>Quartermaster Research & Engineering Center, Natick, Mass. MOISTURE PERMEABILITY INDEX - A NEW INDEX FOR DESCRIBING EVAPORATIVE HEAT TRANSFER THROUGH FABRIC SYSTEMS BY A. E. Woodcock, 16 pp., illus. (Technical Report EP-148) June 1961</p> <p>From theoretical considerations a new clothing parameter, moisture permeability index, has been developed. The existing "clo" formula relating dry clothing insulation and ambient temperature to man's heat loss has been extended to include evaporative heat transfer. This extension indicates a range over which the clothed man may maintain thermal equilibrium. This concept of range applies in all types of environments and thus one theory is applicable to hot, temperate, and cold environments. The theory also indicates the limitations of sweat evaporation as a cooling mechanism.</p> <p>A method is described for measuring moisture permeability index.</p>	<p>Quartermaster Research & Engineering Center, Natick, Mass. MOISTURE PERMEABILITY INDEX - A NEW INDEX FOR DESCRIBING EVAPORATIVE HEAT TRANSFER THROUGH FABRIC SYSTEMS BY A. E. Woodcock, 16 pp., illus. (Technical Report EP-148) June 1961</p> <p>From theoretical considerations a new clothing parameter, moisture permeability index, has been developed. The existing "clo" formula relating dry clothing insulation and ambient temperature to man's heat loss has been extended to include evaporative heat transfer. This extension indicates a range over which the clothed man may maintain thermal equilibrium. This concept of range applies in all types of environments and thus one theory is applicable to hot, temperate, and cold environments. The theory also indicates the limitations of sweat evaporation as a cooling mechanism.</p> <p>A method is described for measuring moisture permeability index.</p>	<p>Quartermaster Research & Engineering Center, Natick, Mass. MOISTURE PERMEABILITY INDEX - A NEW INDEX FOR DESCRIBING EVAPORATIVE HEAT TRANSFER THROUGH FABRIC SYSTEMS BY A. E. Woodcock, 16 pp., illus. (Technical Report EP-148) June 1961</p> <p>From theoretical considerations a new clothing parameter, moisture permeability index, has been developed. The existing "clo" formula relating dry clothing insulation and ambient temperature to man's heat loss has been extended to include evaporative heat transfer. This extension indicates a range over which the clothed man may maintain thermal equilibrium. This concept of range applies in all types of environments and thus one theory is applicable to hot, temperate, and cold environments. The theory also indicates the limitations of sweat evaporation as a cooling mechanism.</p> <p>A method is described for measuring moisture permeability index.</p>
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QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
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ENVIRONMENTAL PROTECTION RESEARCH DIVISION

Technical Report
EP-149

MOISTURE PERMEABILITY INDEX -
A NEW INDEX FOR DESCRIBING EVAPORATIVE
HEAT TRANSFER THROUGH FABRIC SYSTEMS

A. H. Woodcock, Ph.D.

Biophysics Branch

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FOREWORD

In 1941 the clo formula added tremendous impetus to the science of cold-weather clothing by describing dry insulation in precise quantitative physical terms rather than comparatively vague qualitative ones. No such parameter has been available for describing the evaporative heat transfer characteristic of clothing, which is the major factor in heat loss. As a result, the clo formula could not be used in any environments where the man was sweating.

The stress of a hot environment can be predicted with reasonable accuracy on a nude man. However, there has been no way of extending the prediction to men wearing various types of clothing. To the Quartermaster Corps this lack of guidance is a serious shortcoming, since one of its missions is to provide suitable clothing for the soldier for all environments.

In this paper, a new index is developed and the dry insulation, or clo, formula is extended to include those cases where sweat evaporation is important. This supplies the missing factor in the man-clothing-environment complex and allows hot-weather clothing systems to be quantitatively described.

AUSTIN HENSCHEL, Ph.D.
Chief
Environmental Protection Research
Division

Approved:

DALE H. SIELING, Ph.D.
Scientific Director
QM Research & Engineering Command

MERRILL L. TRIEB
Brigadier General, USA
Commanding
QM Research & Engineering Command

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ABSTRACT

From theoretical considerations a new clothing parameter, moisture permeability index, has been developed. The existing "clo" formula relating dry clothing insulation and ambient temperature to man's heat loss has been extended to include evaporative heat transfer. This extension indicates a range over which the clothed man may maintain thermal equilibrium. This concept of range applies in all types of environments and thus one theory is applicable to hot, temperate, and cold environments. The theory also indicates the limitations of sweat evaporation as a cooling mechanism.

A method is described for measuring moisture permeability index.

MOISTURE PERMEABILITY INDEX -
A NEW INDEX FOR DESCRIBING EVAPORATIVE
HEAT TRANSFER THROUGH FABRIC SYSTEMS

1. Introduction

The introduction by Gagge, Burton, and Bazett (3) of the quantitative concept of thermal insulation gave a great impetus to the science of clothing. Not only did it establish a quantitative measure, but also, and perhaps more important, it provided a prediction formula for the man-clothing-environment complex by relating heat loss and skin temperature to clothing insulation and to environmental temperature. The formula was, however, limited to dry heat loss; the lack of an evaporative heat loss factor made it unsuitable when sweating occurred, such as in hot environments or in cold environments when the man is exercising.

The thermal balance between man and the environment without the clothing factor has been discussed in earlier reports (7,9). In these studies, the effects of temperature, humidity, wind, and radiation were related to heat dissipation, skin temperature, and skin humidity for the nude man. Factors were included for clothing and an indication given of how clothing will affect man's thermal balance. But the parameters were expressed by hypothetical symbols which are not readily measured in numerical terms for specific clothing materials.

It is, of course, well known that clothing impedes the transfer or escape of moisture vapor which is formed by the evaporation of sweat at the skin. Moisture vapor which accumulates within clothing raises the local humidity and thus tends to slow down the rate of sweat evaporation and the accompanying removal of heat from the skin surface.

Several investigators have attempted to estimate this impedance to removal of moisture vapor by measuring the resistance to moisture diffusion of textiles in still air. This work culminated in the classical paper of Whelan et al (6), who established a relationship between fabric structure and the resistance to moisture diffusion. However, these investigators measured the resistance to diffusion through the textile from one mass of still air to another. This value may be quite different from that for the impedance to evaporation from a moist surface, through a textile fabric placed over it, to an environmental mass of air which is generally moving. Under the latter condition, there is not only diffusion of moisture vapor through the fabric but also mass movement of air through, over, and even under it which carries off the moisture vapor. Indeed, although the results of moisture diffusion experiments are perfectly valid, they cannot be readily applied to the sweating man-clothing-environment complex, in which not only diffusion of moisture vapor but also its transfer by convection takes place.

Physiologists who have investigated heat stress in clothed man (4,5) have invariably described the clothing in qualitative terms, since there has been no quantitative figure (such as the clo unit of insulation) by which clothing properties could be evaluated. Belding and Hatch (1) conclude that heat stress indices must be made on a no-clothing basis since "limitations of available knowledge" prevent the use of a clothing factor.

The aim of this report is to supply the required clothing parameter, to indicate its relationship in the man-clothing-environment complex, and to outline the technique of measurement. The new parameter, which is an index of the permeability of clothing to moisture vapor, will be termed moisture permeability index, or simply "permeability index," and denoted by " i_m ." It will be shown that it can be included as a second clothing parameter (dry thermal insulation being the first) in the general equation for heat transfer between the skin and the environment.

Such an equation can be used by the environmental scientist in predicting ranges of environment and metabolic activity in which thermal equilibrium can be maintained, rather than the single environmental temperature or heat loss given by the older clo formula of Gagge et al (3). The permeability index can also be used by the clothing technologist as a figure of merit for clothing or fabrics. In addition, the index and its development is of use in promoting understanding of the mechanism of heat loss from the skin of a man not only when clad in light clothing in warm environments, but also when clad in thick or heavy clothing in temperate or cold environments.

2. Theory

The formula relating dry heat loss through clothing from the skin to the environment is

$$H_d = \frac{T_s - T_a}{I} \quad \text{Equation 1}$$

where:

H_d = rate of dry heat loss per unit area
 T_s = skin temperature
 T_a = ambient temperature
 I = insulation, or thermal resistance of the clothing plus overlying air layer

This is the "clo" formula of Gagge et al (3) except for omission of the numerical coefficient used when expressing I in clo units. It can be seen that for a given heat loss H_d , skin temperature T_s , and insulation I , there is one, and only one, value of the ambient temperature T_a . Actually, however, a human can maintain thermal balance at higher ambient temperatures than specified by this formula since additional heat can be dissipated by evaporation of sweat. Thus, there is a range of environmental

temperatures over which thermal equilibrium can be maintained and equation 1 gives only its lower limit.

If heat transfer occurs by both dry and evaporative means, then

$$H = H_d + H_e \quad \text{Equation 2}$$

where:

H = total rate of heat transfer per unit area
 H_e = rate of evaporative heat transfer per unit area

The evaporative heat transfer H_e can be expressed by

$$H_e = \frac{(p_s - p_a)}{E} \quad \text{Equation 3}$$

where:

p_s = the vapor pressure of the skin
 p_a = the vapor pressure of the air
 E = the resistance to evaporative heat transfer per unit of vapor pressure difference across clothing plus overlying air layer

Equation 2 can then be rewritten (substituting value of H_d from equation 1 and value of H_e from equation 3) as:

$$H = \frac{T_s - T_a}{I} + \frac{p_s - p_a}{E} \quad \text{Equation 4}$$

In this equation H , T_s , and p_s are the man (or physiological) parameters, T_a and p_a are environmental parameters, and I and E are parameters determined by the clothing plus overlying air layer.

Equation 4 applies not only to skin covered by clothing but to any surface which is supplied with heat and moisture which causes p_s to differ from p_a .

The value of E may be determined by placing the clothing or fabric system on an unheated or wetted surface and allowing it to come into equilibrium with its surroundings. H in equation 4 is then equal to zero and all other parameters except E can be measured. T_a and p_a are the ambient temperature and vapor pressure, T_s is the temperature attained by the surface, and p_s is the saturated vapor pressure at T_s . The insulation I of the clothing system can be determined by conventional means.

An evaporative heat transfer characteristic for a textile which is more definitive than E can be derived as follows by rewriting equation 4:

$$H = \frac{1}{I} \left[(T_s - T_a) + \frac{I}{E} (p_s - p_a) \right] \quad \text{Equation 4a}$$

For a bare, wetted, unheated surface in a rapidly moving air stream (i.e., a wet-bulb thermometer), H equals zero and equation 4a becomes

$$\frac{I'}{E'} = \frac{T_a - T_w}{p_w - p_a} \quad \text{Equation 4b}$$

where:

T_w = the temperature of the wet-bulb thermometer

p_w = the saturated vapor pressure of water at the wet-bulb temperature

I' = the value of I when applied to a wet-bulb thermometer

E' = the value of E when applied to a wet-bulb thermometer

The ratio I'/E' is a constant (or very nearly so) and was denoted by S in an earlier report (9). If the ratio I/E to I'/E' is denoted by i_m , the permeability index, equation 4 can be written in the form

$$H = \frac{1}{I} [T_s - T_a] + i_m S (p_s - p_a) \quad \text{Equation 5}$$

The parameter S is a constant equal to 20° per mm Hg vapor pressure or 3.6° per mm Hg. S is really a conversion factor which converts a vapor pressure difference to an effective temperature difference.

The permeability index, i_m , takes the form of an efficiency factor. It has a theoretical range from unity (for the ideally permeable system) to zero (for the completely impermeable one). It does not include thickness or insulation value and it is also a dimensionless quantity, so that it has the same value regardless of the system of units used. It is felt, therefore, that i_m is a more satisfactory term by which to describe moisture permeability than E, which increases with thickness of clothing and has different numerical values depending on the system of units used.

Heat loss from the body when not sweating is then given theoretically by the original formula of Gagge et al (3)

$$H_d = \frac{3.09}{I} (T_s - T_a) \quad \text{Equation 6}$$

where:

H_d is in kg-cal/m²/hr

I is in clo units

T_s and T_a are in degrees F

and 3.09 is a numerical factor put in to accommodate the clo unit.

When sweating occurs, this original formula is expanded to the more general form (from equation 5)

$$H = \frac{3.09}{I} [(T_s - T_a) + 1.8 (p_s - p_a)] \quad \text{Equation 7}$$

In using equation 7 for prediction purposes, T_s is generally taken at some standard value (Belding and Hatch (1) have selected 95°F). The value of p_s reaches a maximum value, about 90% of the vapor pressure of water at skin temperature (7), when the skin is wet with sweat.

Equations 6 and 7 thus define, for any given skin temperature and ambient conditions, a range over which heat loss can be varied by sweating to compensate for changes in metabolic heat production so that thermal equilibrium can be maintained.

Alternatively, for a given skin temperature and fixed heat loss (constant metabolism) the equations define a range of ambient conditions in which thermal equilibrium can be maintained.

At intermediate points within the range, the rate of sweating is less than the maximum which can be evaporated and in consequence the secreted sweat is evaporated immediately and the skin appears dry. It should perhaps be pointed out that in most hot environments the amount of sweat which can be secreted without excessive strain is adequate for cooling, provided it can be evaporated. Only in extremely hot dry environments, in which ambient temperatures are well above skin temperature, are evaporative requirements excessively high and a normal man limited in cooling capacity by insufficient sweat secretion (9).

3. Measurement of permeability index

The apparatus (Fig. 1) used for measuring permeability index was a vertical 6-inch-diameter cylinder with a wetted surface. It consisted of a copper test section 6 inches long with 3-inch copper guard rings to prevent end losses. At the top of the cylinder was an annular cup or water reservoir of plastic whose outside diameter was also 6 inches. A fine linen covering was fitted tightly over the whole cylinder with the end dipping into the water reservoir. Water from the reservoir wicked up this linen to the rim of the cup and then down over the cylinder with a small excess dripping off the bottom. The rate of flow of water was only slightly in excess of the amount required to keep it wet and so slow that it came into temperature equilibrium before flowing very far down the cylinder. Since such a cylinder would tend to wet the insulation or fabric system placed over it, it was covered with a single layer of 300 P.T. cellophane. This cellophane, which was thoroughly washed with distilled water, had an outer surface which was "dry" in the sense that no free water could be blotted from it. However, the cellophane transferred moisture so readily that repeated tests indicated it had a vapor pressure indistinguishable from that of distilled water.

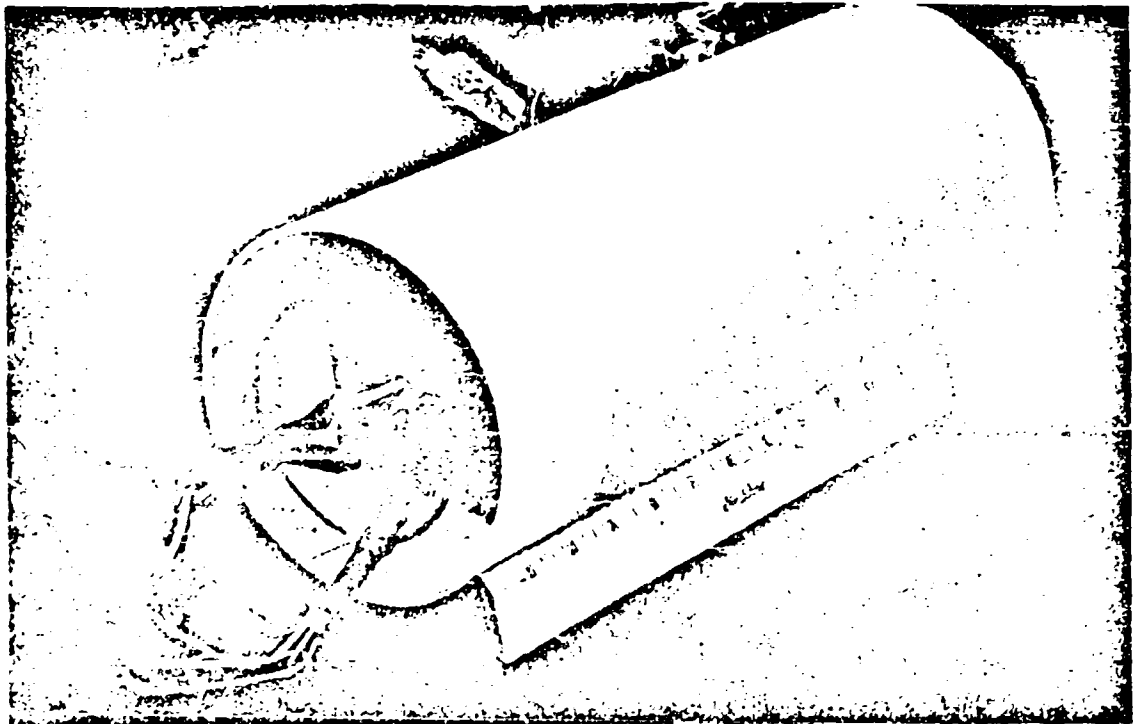


Figure 1. Moistened cylinder showing water reservoir and linen wick at top.

This cylinder assembly, covered with the fabric or the insulation system to be studied, was placed in a small wind tunnel in a well-insulated room. The room was equipped with wet- and dry-bulb thermometers consisting of two copper-constantan thermocouples, one with a wetted wick placed at the inlet of a small blower. Since wet-bulb and dry-bulb temperatures did not need to be at any specific values, but only to be constant and known, the room was used without air conditioning. The room changed temperature by less than 0.2°F per day (this is more constant than an air conditioned room in which temperature and humidity oscillate about a fixed value).

When equilibrium was established, dry-bulb, wet-bulb, and cylinder temperatures were measured; from these, T_B , p_B , T_g , and p_g were obtained. Then i_m was calculated using equation 7 and assuming H to be zero.

4. Typical permeability indices

Typical results are given only to indicate the general magnitude of the permeability index for both the bare cylinder and for a sample fabric.

Values for the bare cylinder are shown in Table I.

TABLE I

PERMEABILITY INDEX FOR BARE CYLINDER

	Wind Speed (ft/min)		
	50	70	100
Permeability index	0.63	0.68	0.70

It will be seen that the permeability index decreases with decreasing wind. This decreasing wind results in a thicker "still air layer" surrounding the cylinder; this offers greater impedance to evaporation. Convection losses from the cylinder are decreased in proportion to evaporation (9) but R_2 is made up of both convection and radiation and the latter is not affected by wind. Hence, the ratio of evaporative to dry heat loss decreases and the permeability index is reduced.

The effect of spacing a 6-oz khaki poplin away from the cylinder is shown in Table II. Results are given for both a stationary cylinder, representing a stationary man, and a cylinder moved back and forth about 2-1/2 inches at 50 cycles per minute to simulate a walking man.

TABLE II

PERMEABILITY INDEX (AT VARIOUS SPACINGS FROM
THE CYLINDER) OF 6-OZ KHAKI POPLIN

(Wind Speed 50 ft/min)

Covering Diameter (in.)	Nominal Spacing (in.)	Permeability Index	
		Moving	Stationary
6	0	0.51	0.49
7	1/2	0.51	0.45
8	1	0.55	0.47
10	2	0.56	0.47

Table II indicates that the permeability index at 50 ft/min is less for the "clothed" cylinder than for the bare one (0.63) indicating that the presence of the poplin increased resistance to evaporative heat loss more than it increased the resistance to dry heat loss. The effect of moving the cylinder is to increase the permeability index, which is as expected since this increases air movement. Increasing the spacing on the moving cylinder increases the permeability index, presumably because of increased air flow between the covering and the cylinder. When the cylinder is not moving, the effect of spacing appears negligible at this low wind speed where air movement in the air space is very slight.

While the results quoted here are somewhat limited, it can be seen that an increase in air movement, whether by wind (Table I) or by movement of the body (Table II), tends to increase the permeability index. When applied to hot-humid environments, this indicates that a fan not only increases dry heat transfer but also increases evaporative heat transfer by an even greater percentage.

5. Discussion

In assessing the importance of the permeability index, two viewpoints will be used. The theoretical viewpoint will be discussed first, then the practical application.

a. Theoretical implications

From the theoretical viewpoint, the permeability index supplies the missing parameter required for considering clothed man's thermal balance. The concept of thermal insulation indicated the requirements to keep man from being chilled in a cold environment, but it could give no clue as to why heavily-clad men exercising in a cold environment could so readily become overheated. With the introduction of the permeability index, a range over which man can maintain thermal equilibrium has been established for which the thermal insulation concept provides the lower limit. This is a shift from the concept that the purpose of clothing is to keep a man as warm as possible, to the one in which the purpose of clothing is to keep him in thermal equilibrium.

Moreover, the thermal equilibrium concept was generally applied to cold environments, occasionally to temperate ones, and never to warm or hot environments. As stated by Belding and Hatch (1) no quantitative parameters could be applied to hot-weather clothing, since these parameters were not known. The introduction of permeability index does more than supply the important missing parameter; it allows a pair of parameters to describe the effect of clothing through a unified concept which is the same whether the environment is hot, cold, or temperate. No longer is it necessary for heat stress to be studied using nude men or those clad in clothing which is described only by qualitative terms, such as "light." It is now theoretically possible to study heat stress on vigorously exercising men in temperate and cold environments as well as in hot environments.

Furthermore, this development points the way to interrelating environmental factors (such as temperature and vapor pressure), physiological factors (such as skin temperature and skin vapor pressure) and clothing factors (such as insulation and permeability index) to give a quantitative relationship for the man-clothing-environment complex. Perhaps most important is the development of the quantitative concept that there is a range of environments or alternatively a range in rate of heat loss, corresponding to different activities, over which man can maintain thermal equilibrium.

Figure 2 shows the calculated environmental limits for thermal equilibrium with a heat loss of 100 kg-cal/m²/hr and an insulation of 2 clo as a function of permeability index. It will be seen that, in order to have clothing which is adaptable to a wide range of environments, the permeability index must be high. It was a low permeability index which caused the vapor barrier uniforms to be so excessively hot for exercising men.

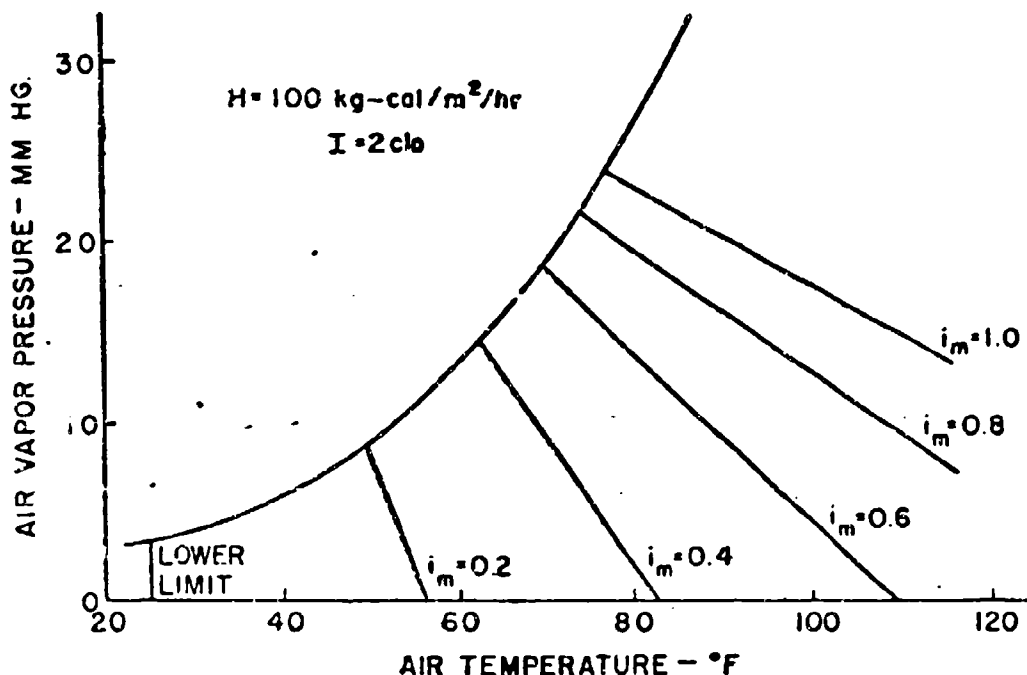


Figure 2. The upper limits of ambient conditions for various values of permeability index.

Equation 7 can be used as follows to show that relatively light clothing provides the greatest ranges. This equation can be written for two rates of heat loss, H' and H'' as follows:

$$IH' = 3.09 [T_s' - T_a] + i_m S (p_s' - p_a)$$

and

$$IH'' = 3.09 [T_s'' - T_a] + i_m S (p_s'' - p_a)$$

where the superscripts indicate the respective skin conditions.

Subtracting, $I (H' - H'') = 3.09 [(T_s' - T_s'') + i_m S (p_s' - p_s'')]$

or $I \Delta H = 3.09 [\Delta T_s + i_m S \Delta p_s]$ Equation 8

It will be noted that this equation does not contain any environmental parameters. ΔT_s represents a range of variation in skin temperature, and Δp_s a range of variation in skin vapor pressure (which is controlled by sweating).

Equation 8 has been used to plot lines of constant $I \Delta H$ as a function of skin vapor pressure and skin temperature (Fig. 3). These are plotted at intervals of 40 clo kg-cal/m²/hr for two permeability indices (0.6 solid line, and 0.4 dashed line). As an illustration of the use of this figure, a change in skin conditions from 88°F and 2.3 mm Hg (point A) to

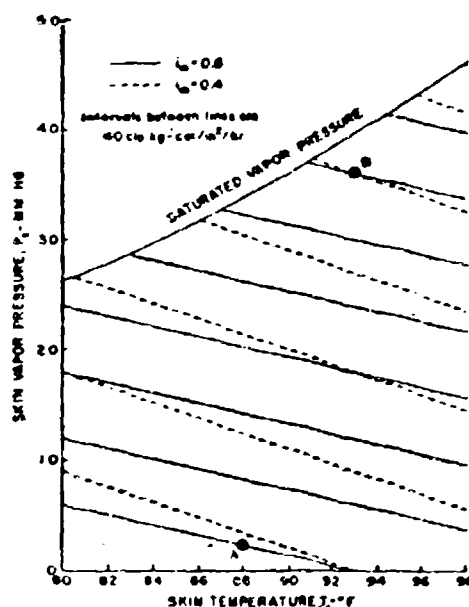


Figure 3. Effect of changes in skin vapor pressure and/or skin temperature on heat loss at any insulating value.

93°F and 36 mm Hg (point B) with i_m of 0.6 corresponds to 6 intervals of 40, or 240 clo kg-cal/m²/hr. This, in a 3 clo uniform, represents a change in heat loss of 240/3 or 80 kg-cal/m²/hr; in a 1/2 clo uniform it represents a change of 480 kg-cal/m²/hr. These values hold regardless of environmental conditions, except that skin vapor pressure must, of course, be at least as high as ambient vapor pressure. They confirm the hypothesis that light clothing permits the greatest i_m , or that in cold environments the least clothing consistent with warmth is desirable.

With a permeability index of 0.4 a similar change in skin conditions (from point A to point B) produces an $I \Delta H$ of only 4.1 x 40, or 164 clo kg-cal/m²/hr, showing that permeability index should be as high as possible.

Since skin vapor pressure can be no lower than ambient vapor pressure, it will be seen that high humidities produce a limited range in which equilibrium can be maintained. This also is illustrated by Figure 3.

b. Practical applications

From the practical viewpoint, there are some limitations as there were in the original dry insulation concept. It should be pointed out that

the concept of permeability index is based on equilibrium conditions and that in cold environments these may not occur (8). In addition, it has been shown that dry insulation is not uniform at all points on a cylinder exposed to wind (2). Permeability index is likewise not expected to be uniform. It is customary in such cases to use an average or integrated value, although recent findings have cast some doubt on the strict validity of doing so (9).

Nevertheless, permeability index is of considerable practical use. It is particularly useful to the textile technologist and clothing designer as a figure of merit on which to assess his product. Not only does it allow for ranking of textiles but, by applying equation 7, the technologist can obtain a measure of how much he has improved his product.

6. Acknowledgments

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7. References

1. Belding, H.S. and T.F. Hatch. Index for evaluating heat stress in terms of resulting physiological strains. A.S.P.A.E. Journal Section, Heating piping and air conditioning, pp 129-136, Aug 1955.
2. Fonseca, G.F., J.R. Breckenridge, and A.H. Woodcock. Wind penetration through fabric systems. Env Prot Res Div Tech Rpt EP-104, ON R&E Command, Natick, Mass., 1959.
3. Gagge, A.P., A.C. Barton, and H.C. Bazett. A practical system of units for the description of the heat exchange of man with his environment. Science 94:428, 1941.
4. McArdle, B., W. Dunham, E.H. Holling, W.S.S. Ladell, J.W. Scott, M.L. Thomson, and J.S. Weiner. The prediction of the physiological effects of warm and hot environments. Med. Res. Council, Great Britain, R.M.P. 47/391 H.S. 194, 1947.
5. Robinson, S., E.S. Turrell, and S.D. Gerking. Physiologically equivalent conditions of air temperature and humidity. Am. J. Physiol. 143:21, 1945.
6. Whelan, M.E., L.E. MacHattie, A.C. Goodings, and L.H. Turl. The diffusion of water vapor through laminae with particular reference to textile fabrics. Text. Res. J. 25:197, 1955.

7. Woodcock, A.H., R.L. Pratt, and J.R. Breckenridge. Heat exchange in hot environments. Env Prot Res Br Rpt No 183, OQMG, Jan 1952.

8. Woodcock, A.H. Wet-cold II: A theoretical interpretation of the sensation of damp cold experienced by clothed man. Env Prot Res Br Rpt No 199, OQMG, Feb 1953.

9. Woodcock, A.H., J.J. Powers, and J.R. Breckenridge. Man's thermal balance in warm environments. Env Prot Res Div Tech Rpt EP-30, QM R&D Command, Natick, Mass., Jul 1956.

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Department of the Army
Washington 25, D. C.
- 1 Commanding General
Philadelphia QM Depot, U. S. Army
200 South 20th Street
Philadelphia, Pa.
- 1 Commandant
QM Food & Container Institute for the
Armed Forces, U. S. Army
183 W. Pershing Rd.
Chicago, Illinois
- 1 Commanding Officer
QM R&E Field Evaluation Agency, U. S. Army
P. O. Box 1, Virginia
Attn: Chief, TEO
- 1 QM Liaison Officer, WOOL-3
Wright Air Development Center
Wright-Patterson AF Base
Dayton, Ohio
- 1 Commandant
The QM School
P. O. Box 1, Virginia
Attn: Library
- 1 Commanding General
Frederick Arsenal, P.O. Box 1, Pa.
Attn: Engr. Psychology Div. (L2)
- 1 Asst. Army Electronic Proving Ground
P. O. Box 1, Arizona
Attn: Aviation & Meteorological Dept.
Tech. Information Br.
Deputy Chief for Meteorology
- 1 Commanding General
The Engineer Center
P. O. Box 1, Va.
- 1 Commanding Officer
Diamond Ordnance Fuze Labs.
Washington 25, D. C.
Attn: Tech Reference Section
(OSDTL-GL2)
- 1 Commanding General
Aberdeen Proving Ground
Aberdeen, Maryland
- 1 Chief Signal Officer
Department of the Army
Washington 25, D. C.
Attn: Res. & Dev. Div.

ARMY (Cont)

- 1 Commanding Officer
Signal Corps Bldg. 10th
P. O. Box 1, N. C.
- 1 Office of Chief of Engineers
Department of the Army
Temp. Bldg. T-7, Gravelly Point
Washington 25, D. C.
Attn: Research & Dev. Div.
- 1 CO, Chemical Warfare Laboratories
Army Chemical Center, Maryland
Attn: Technical Lab. Laboratory
- 1 Chief Chemical Officer
Department of the Army
Bldg. T-7, Gravelly Point
Washington 25, D. C.
Attn: Res. & Dev. Div.
- 1 SEC. Hq., Medical Research Lab.
Plainsboro Army Hospital
Barnes, Colorado
(1-Dr. Friedman)
- 1 Armed Forces Institute of Pathology
Washington 25, D. C.
- 1 Chief, Armed Services Medical
Procurement Agency
24 South St., Brooklyn, N. Y.
Attn: Property Officer
Market Reg. INDEX 25
- 1 Chief of Transportation
Department of the Army
Temp. Bldg. T-7, Gravelly Point
Washington 25, D. C.
- 1 Commanding Officer
Transportation Res. & Eng. Command
U. S. Army
P. O. Box 1, Virginia
Attn: Tech Services Div.
- 1 The Army Library
Postage Bldg.
Washington 25, D. C.
- 1 Commandant, Command to General Staff
College
P. O. Box 1, Kansas
- 1 Commandant, U. S. Military Academy
West Point, New York
- 1 Commanding Officer, Detachment Arsenal
24th Van Dyke St., Commerce, Mich.
Attn: Res. & Engr. Div.
- 1 Commanding General
Hq., U. S. Army Medical R&D Command
Mills Navy Bldg.
Washington 25, D. C.
Attn: HPAFP Research Branch
- 1 Commander
QM Intelligence Agency, U. S. Army
Washington 25, D. C.
- 1 Executive Director
Military Clothing and Textile Supply Agency
200 S. 20th St., Pullman, W. Va.
- 1 Commanding Officer
QM R&E Field Evaluation Agency, U. S. Army
Airborne Systems Test Div.
Yuma Test Station
Yuma, Arizona

ARMY (Cont)

- 1 Commanding Officer
Cold Weather & Mountain Substation
P.O. Box 1
Fort Greely, Alaska
- 1 Commanding Officer
Fort Greely, Alaska
Attn: Tech Serv. Div.
- 1 Department of /Air Force
Box 1, USAF, Wash 25, D. C.
(1 DC/8 Material, 1 DC/8 Dev.)
- 1 Director
Air University Library, Attn: 908
Maxwell AFB, Alabama
- 1 Commandant
USAF School of Aviation Medicine
Randolph AP Base
Randolph Field, Texas
- 1 Commander, Arctic Aeromedical Lab
APO 72, Seattle, Washington
- 1 Commander
Air Res. & Dev. Command
Attn: R&D Div. (1 Tech Lab. Br.)
Andrews AP Base, Washington 25, D. C.
- 1 Commander
Wright Air Development Center
Wright-Patterson AF Base, Ohio
Attn: Tech Library
- 1 Commander
Strategic Air Command
Offutt AP Base, Nebraska
- 1 Chief, Medicine Div.
Air Development Center
Aero-Medical Lab.
Wright-Patterson AF Base, Ohio
Attn: Dr. Barry C. Dyer
- 1 Commander
AF Cambridge Research Center
Air Research & Development Center
Laurence G. Hanscom Field
Bedford, Mass.
Attn: CRTOTT-3

NAVY

- 1 Director
Naval Research Laboratory
4th & Constitution St., S. W.
Washington 25, D. C.
- 1 Chief, Bureau of Ordnance
Department of the Navy
Washington 25, D. C.
Attn: R&D Div.
- 1 Naval Medical Research Institute
National Naval Med. Res. Center
Bethesda, Md.
- 1 Chief of Naval Research
Washington 25, D. C.
Attn: Code 6053
- 1 Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.
Attn: Code 28
- 1 Chief, Bureau of Med. & Surgery
Dept. of the Navy, Wash 25, D. C.
Attn: Code 29

NAVY (Cont)

- 1 Commander, U. S. Naval Civil. Test
Station, Chalmers Lab., Calif.
Attn: Code 702
- 1 Chief, Bureau of Aeronautics
Dept. of the Navy, Wash 25, D. C.
Attn: Code 45 58
- 1 Chief, Bureau of Supplies & Accounts
Department of the Navy
Washington 25, D. C.

CONARC

- 1 C.O., U. S. Continental Army Command
P. O. Box 1, Va.
- 1 President
U. S. Army Artillery Bd.
P. O. Box 1, Ohio
Attn: ATRO
- 1 President
US Army Artillery Board
P. O. Box 1, Ky.
Attn: ATRO
- 1 President
U. S. Army Infantry Bd.
P. O. Box 1, Ohio
Attn: ATRO
- 1 President
U. S. Army Air Defense Bd.
P. O. Box 1, Texas
Attn: ATRO
- 1 President
U. S. Army Airborne and Electronics Bd.
P. O. Box 1, N. C.
Attn: ATRO
- 1 President
U. S. Army Aviation Bd.
P. O. Box 1, Ala.
Attn: ATRO
- 1 Commanding Officer
U. S. Army Arctic Test Board
P. O. Box 1, Alaska
Attn: ATRO

BOARDS & COMMITTEES

- 1 Army Committee on Environment
Chief, Research & Development
Postage, Washington, D. C.
- 1 Armed Forces Post. Control Bd.
Walter Reed Army Med. Center
Postage Box 1
Main Bldg.
Fort Detrick, Maryland
- 1 Army Research Committee
Chief, Research & Development
Postage, Washington, D. C.

MISCELLANEOUS

- 1 National Research Council
200 Constitution Ave., Washington, D. C.
Attn: Advisory Bd. on QM R&D
- 1 Armed Services Technical Information Agency
Arlington Hall Station
Arlington 25, Va.
Attn: TIPS
- 1 Oil and Exchange Division
Library of Congress
Washington 25, D. C.
- 1 U. S. Department of Commerce
Weather Bureau Library, Washington, D. C.
- 1 Central Intelligence Agency
Collection & Dissemination
Washington 25, D. C.
- 1 National Library of Medicine
Washington 25, D. C.
- 1 General Information
Randolph Hospital
Postage
Olathe, Missouri
- 1 Marine Corps Education Board
Marine Development Center
Marine Corps School
Quantico, Va.
- 1 Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.
Attn: Tech Ref. Sec. (INDEX 25)
- 1 U. S. Department of Agriculture Library
Washington 25, D. C.
- 1 Commandant
Industrial College of the Armed Forces
P. O. Box 1, Washington 25, D. C.
- 1 QM Representative
Army Command and General Staff College
Department of the Army
P. O. Box 1, Kansas